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Properties of premixed hydrogen/propane/air flame in ceramic granular beds

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ABSTRACT

This study investigated how various H_2 concentrations of fuel mixed with a ceramic granular bed (CGB) affect the propagation characteristics of a premixed C_3H_8/air flame. The results showed that at low firing rates ($\Gamma < 1.5$ kJ/s), as Γ increased, adding H_2 exerted little effect on the flame temperature and absolute flame front velocity (S_{ab}); however, at high Γ ($\Gamma > 1.5$ kJ/s), as Γ increased, adding H_2 caused a significant decrease in the flame temperature and a substantial increase in $S_{ab.}$ Thus, heat transfer was not obvious, and the flame reaction zone was relatively broad. Although adding H_2 moved the flame reaction zone upstream, the heat transfer mechanism reduced the effect that resulted from adding H_2 under low Γ conditions. Because of the characteristics of H_2, the flame reaction zones moved upstream, causing the flame thickness and heat loss to increase. Adding H_2 decreased the flame temperature and increased $S_{ab.}$

Introduction

A ceramic granular bed (CGB), with the characteristics of a porous medium burner, is capable of retaining heat and preheating. As such, a premixed flame, when propagated in a CGB, can contribute to excess enthalpy combustion [1], expanded flammability, and reduced emissions [2]. It can be used in the burning of fuels with a low calorific value, to reduce emissions, and to increase combustion efficiency. Combustion is categorized as either mild combustion [3–6], feedback combustion, or high-temperature air combustion (HiTAC) [7], based on the thermal circulation pattern. It enhanced the temperature of the reagent to change the combustion progresses accordingly through the heat recirculation mechanism. Factors affecting the flame propagation characteristics of the porous medium, however, include the heat recirculation mechanism and fuel properties. The heat recirculation mechanism is based on the fuel flow rate, the porosity and conductivity of the medium, and the absorption of materials.

In other words, various fuels and various burners feature distinct combustion patterns. While developing a biomass application technique, developing a low-calorie fuel-combustion method or energy-conversion method is also necessary, such as the fluidized-bed combustion method [8,9] and oil production through fast pyrolysis [10]. Because most of the components of uncondensed gas produced during biomass fast pyrolysis are volatile and moist, the uncondensed fire is cofired with propane to recycle the thermal energy.

CGBs feature heat accumulation and inert and porous properties. When premixed flames pass through a CGB, they transfer heat to the upstream ceramic medium, which subsequently transfers heat to a premixed mixture, causing

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preheating. Premixed flames demonstrate higher propagated velocity and increased stability when transferred in porous medium compared with premixed free flames. The materials and porosities of the porous medium alter the properties of the premixed flame, changing the thermal conduction, convection, and radiation process during heat transfer, thereby influencing the stability, propagation speed, and flammability of the flame [11–16]. Mishra et al. [17] used numerical simulation to explore burners that employ porous media of various materials and porosities; their results showed that low porosity levels increase the volumetric heat transfer coefficient, whereas high porosity increases the extinction coefficient. Using a one-dimensional calculation model, Al-Mamare et al. [18] concluded that in two distinctly fabricated porous media, the flame temperature was lower than the adiabatic flame temperature, the burning rate correlated with heat capacity, and the inert content of the porous medium burners significantly lowered the flame temperature.

The heat transfer characteristics of premixed flame in a porous medium are influenced by the heat transfer mechanisms between the porous medium and the flame, and the components of the mixture. The premixed flame then demonstrates mild combustion, changing the location of the flame reaction zone and the flame thickness. Costa and colleagues investigated the combustion characteristics of porous media [19–22], including those of hydrogen-rich gaseous fuels with a low calorific value [19] and the impact of the velocity profile of a porous medium burner on persistent flammability [20]. They measured OH* chemiluminescence of flames, recorded the propagation properties [21] of flames, and changed the ambient preheating temperature to explore the changes in transmission characteristics resulting from the influence of the preheating temperature [22]. Yang and Hsu [2] used experimental measurement and numerical simulation to analyze the heat transfer mechanisms of a premixed CH_4/air flame in a CGB at various flow rates and equivalence ratios. The results indicated that premixed heat transfer in the CGB increased the flammability limit, enhanced the burning rate and reduced emissions. Although premixed flames can be applied to combust low-calorific-value fuels, their instability restricts the operating range to a specific region in which the premixed flame demonstrates mild combustion and the boundary between the reaction and the preheated zones of the premixed flame is unknown. This further expands the operating range, thus generating the flameless phenomenon. Consequently, thermal conduction and radiation independently govern two distinct operating ranges for preheat recirculation.

Tseng [23] used numerical methods to explore the combustion properties of premixed H_2/CH_4/air in porous medium burners by using various proportions of hydrogen. The findings suggested that when the proportion of hydrogen increased, the thickness of the premixed flame decreased, the burning rate increased, the CO emission slightly increased, and the level of NO_x emissions was higher than for the free flame. Alavandi and Agrawal [24] experimentally examined the transfer mechanism of a lean premixed H_2/CO/CH_4/air flame in two-section porous burners. When the proportion of H_2/CO in the premixed flame increased, the emission levels of CO and NO_x decreased; the presence of high H_2/CO in the flame decreased the temperature to near the lean blow-off limit. Mendes et al. [25] employed numerical methods to inspect the stability of ultra-lean H_2/CO flames in porous medium burners. The results showed that the volume ratio, inlet mixture temperature and H_2/CO equivalence ratio all influenced flame stability. The aforementioned studies demonstrated that the use of porous medium burners increases the flammability, burning rate, and flame stability of hydrocarbon fuels. Ayoub et al. [26] added H_2 to premixed CH_4/air, and used laboratory-grade furnaces to explore the properties of the premixed flame in a mild combustion regime. Adding H_2 to CH_4/air reduced both NO_x and CO_2 emissions, primarily because H_2 has high diffusivity and reactivity.

According to these studies, using distinct CGB burners changes the heat transfer mechanism by altering the flames, bed qualities, and premixed combinations. The H_2 concentration affects the propagation characteristics of premixed H_2/CH_4/air flames in porous medium burners [27]. Several previous studies [19,22,23,25–29] have investigated the changes in the transfer characteristics and flame structure resulting from the presence of H_2. Changes in the flame characteristics influence the heat transfer mechanism of premixed flames because of the following factors: (1) H_2 concentration affects the transfer characteristics of premixed H_2/CH_4/air flames when various preheating and transferring methods are applied; (2) the diffusivity and reactivity of H_2 in a preheated environment affect the heat transfer characteristics; and (3) the heat transfer characteristics in a high-temperature environment alter the flame structure. In general, heat transfer mechanisms are related to the porosity and material characteristics of the porous medium burner and the fuel types used [2,23].

In the aforementioned studies, the combustion characteristics of a porous media were mostly explored with a premixed methane/air flame. In addition to the change in the thermal transmission mechanism, it was observed that gas transport and gas dispersion exerted an effect on wave propagation but gas transport was not significant when premixed methane/air was used. Therefore, in the present study, experimental and numerical simulation was employed to determine how gas influences the propagated characteristics of premixed H2/C3H8/air flames in CGBs.

Experimental and numerical approaches

Experimental setup

The CGB system (Fig. 1) comprised the CGB, a gas supply system and temperature measurement system. The porous medium used for the CGB burner was fabricated by stacking ceramic granules in a steel tube (external diameter 8.5 cm, internal diameter 7.86 cm, and length 100 cm), forming the CGB. The bed length was 20 cm and the average ceramic granule diameter was 5 mm. Ceramic honeycomb boards were installed upstream and downstream of the CGB to rectify and fix the granular bed. The granules (Table 1) [2] demonstrated a specific heating value of approximately 628–700 J/kg K. A porosity of 0.33 was obtained after bed stacking. Three flow meters and control valves were used to regulate H_2, C_3H_8,

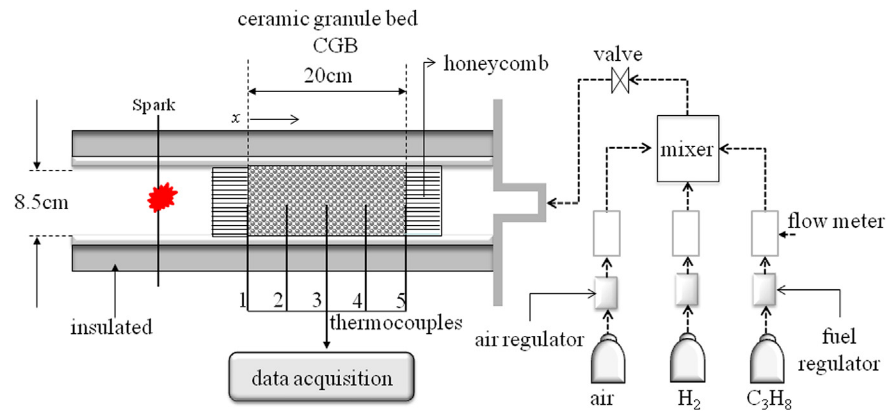

Fig. 1 – Experimental setup of the CGB.

and air supplied to the burner. The gases flowed into a mixer to form premixed fuels. The equivalence ratio of the premixed flames can be calculated as follows:

$$\alpha H_2 + (1-\alpha)\, C_3H_8 + [(5-4.5\alpha)/\phi](O_2 + 3.76N_2) \rightarrow \text{Products}, \quad (1)$$

where α is the percentage of H_2 added to the premixed C_3H_8/air; and ϕ is the equivalence ratio. To calculate the heating values of the input fuels, the following formula was used:

$$\text{firing rate,} \quad \Gamma = HHV_{C_3H_8} \times \dot{m}_{C_3H_8} + HHV_{H_2} \times \dot{m}_{H_2} \quad (2)$$

The H_2 and C_3H_8 used in the study were 99.99% and 99.95% laboratory-grade gases, respectively. Five K-type thermocouples were installed 5 cm apart, upstream of the CGB to measure the temperature of the flame. The data acquisition system (VR18) recorded temperatures at a frequency of 1 Hz.

Numerical method

To examine how the H_2 concentration affects the flame structure of premixed mixtures (H_2/C_3H_8/air), the PREMIX [30] package was employed to determine the flame structure. The reduced kinetic mechanism developed by Peters [31] was employed to simplify the calculation process. The mechanism comprised 31 chemical species and 107 reaction steps. To examine the 1-D flame structure in a CGB containing premixed H_2/C_3H_8/air, the calculation range was set based on the geometrical shapes used in the experiments, and the flame structure of premixed H_2/C_3H_8/air with various u and ϕ values in the CGB was set at an initial temperature of 300 K. To simplify the calculations, the hypothesis, governing equations, and boundary conditions proposed by Yang and Hsu were adopted [2]. In this study, the thermal conduction, convection, and radiation effects generated by CGBs were considered. The thermochemical and transfer characteristics of the gases were obtained using the Chemkin [30] and Tranfit [32] packages. Optically thick approximation [33] was used to calculate the radiation heat transfer among solid substances. The radiation characteristics (e.g., albedo, emissivity, and extinction coefficient) were set at 1.

Table 1 – Physical characteristics of the ceramic granular bed [2].

Physical characteristics of granular bed	
Specific Heat	628–700 J/kg K
Diameter	4–5 mm
Thermal conductivity	1.44 W/m K
Contents	Al_2O_3 (25.03%), SiO_2 (65.97%), Fe_2O_3 (0.6%)

Results and discussion

Experimental measurements and numerical simulations were used to determine the influence of α, ϕ, and u on the combustion characteristics of premixed H_2/C_3H_8/air flames in CGBs. The heat released from premixed flame combustion is transferred to the ceramic granules through thermal convection and radiation, and then to other granules through thermal conduction. Subsequently, the heat is transmitted to the premixed mixture through thermal convection (Fig. 2). Various u and ϕ values influenced the heat transfer mechanism, causing changes to the transfer characteristics of the flame. K-type thermocouples were used to measure flame temperatures, but the recorded temperatures differed from the actual flame temperature because thermal radiation influences thermocouple readings. Therefore, the thermocouples in the current study were corrected to account for the radiation effect [2]. When the flame was situated directly upstream of the CGB, the difference between T_j (temperature of junction) and T_s (temperature solid) was minimal, but as the flame moved further upstream, the difference increased. As the flame moved upstream, passing the thermocouples, the temperature decreased, primarily because the ceramic granules possess a high heat capacity. When the flame passed the thermocouples, the radiation error between the measured and the actual temperature was less than 3%. Although the location at which heat transfer occurs was unaffected by this error, the flame temperature was influenced. Thus, the flame

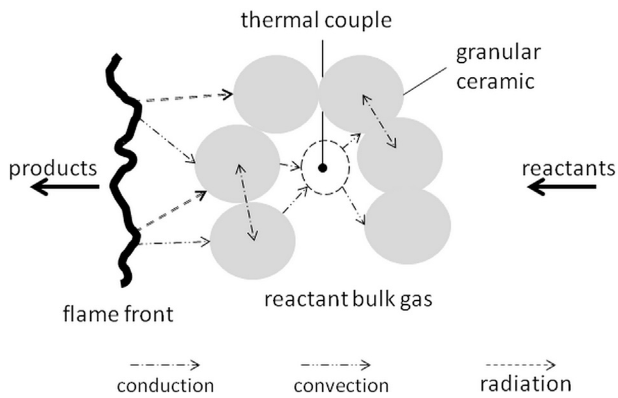

Fig. 2 – A schematic diagram of the heat transfer mechanism of premixed flames in the CGB.

temperatures in the current study were modified to account for radiation error, and the effects of differing H_2 concentration on the transfer characteristics of premixed H_2/C_3H_8/air flames in CGB were then experimentally measured and analyzed using numerical methods.

Experimental results

The influence of H_2 on ceramic-granular-bed temperature distribution

Fig. 3 shows the temperature distribution of a premixed H_2/C_3H_8/air flame in the CGB, where $\phi = 0.6$ and $u = 35.30$ cm/s Fig. 3(a and b) shows the temperature distributions for premixed flames with α values of 0 and 0.3, and Γ values of 1.36 kJ/s and 1.37 kJ/s, respectively. On ignition, the flame gradually shifted from downstream to upstream, entering the CGB. Combustion of the premixed flame released heat, preheating the upstream bed through thermal radiation. When the premixed mixtures flowed from upstream to downstream and passed through the high-temperature CGB, the flame gradually moved upstream because of the thermal convection effect caused by the ceramic granules. The average peak temperature measured by the thermocouple during the flame propagation process was adopted as the flame temperature. The temperature of the premixed H_2/C_3H_8/air flame ($\alpha = 0$) was 1300 K (Fig. 3a), whereas the average temperature of the premixed flame containing H_2 ($\alpha = 0.3$) was slightly lower (1250 K) (Fig. 3b). Whenever thermocouples 2 (TC2) and 4 (TC4) recorded a measurement, the measurement time was also noted. The propagation times of the premixed H_2/C_3H_8/air flame with $\alpha = 0$ and 0.3 were 786 s and 720 s, respectively, indicating that the addition of H_2 resulted in an increased absolute flame front velocity. Comparison of the temperature distribution, as shown in Fig. 3(a and b), shows that the temperatures of the premixed flames to which H_2 was added, increased faster than those to which no H_2 was added. This might have been because the mass diffusivity of H_2 [29] causes it to diffuse into the premixed flame reaction zone, thereby increasing the heat transfer rate. The addition of H_2 decreased global activation energy; consequently, H_2 is readily influenced by the preheating characteristics of the ceramic granules and thus ignites, causing changes to the flame propagation speed and reaction zone of the flame.

The influence of operating conditions on the temperature of premixed H_2/C_3H_8/air flame in the ceramic granular bed

Fig. 4 shows the relationship between the flame temperature, mean velocity, and equivalence ratio of premixed mixtures (H_2/C_3H_8/air) with differing α values (0–0.5) in the CGB. The premixed flame temperature in the CGB was taken

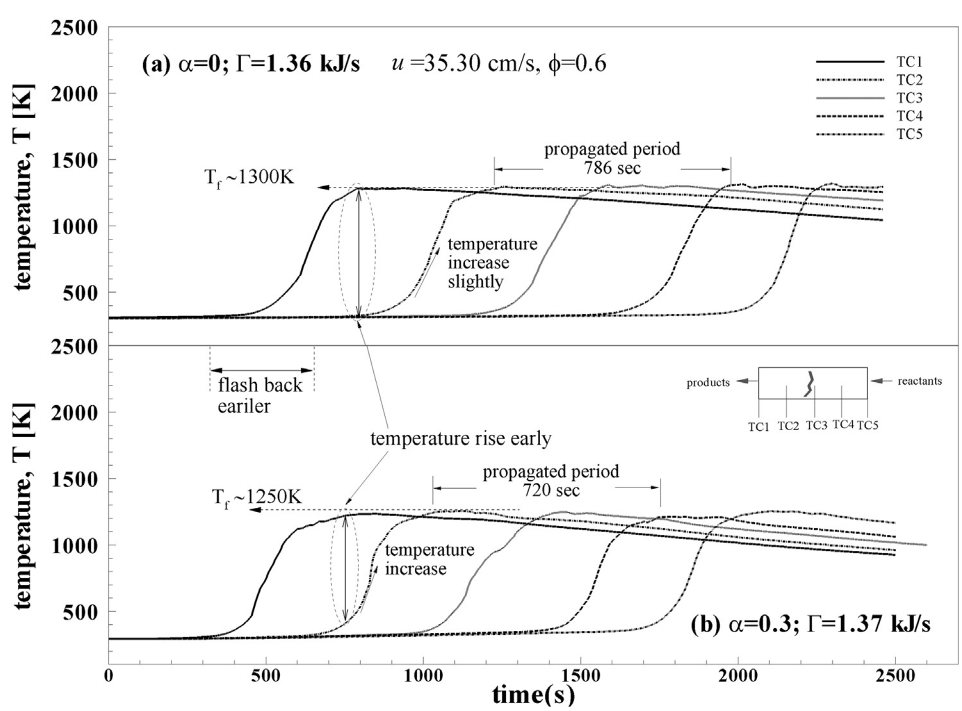

Fig. 3 – Temperature distribution of the premixed H_2/C_3H_8/air flame in the CGB: (a) $\alpha = 0$; (b) $\alpha = 0.3$.

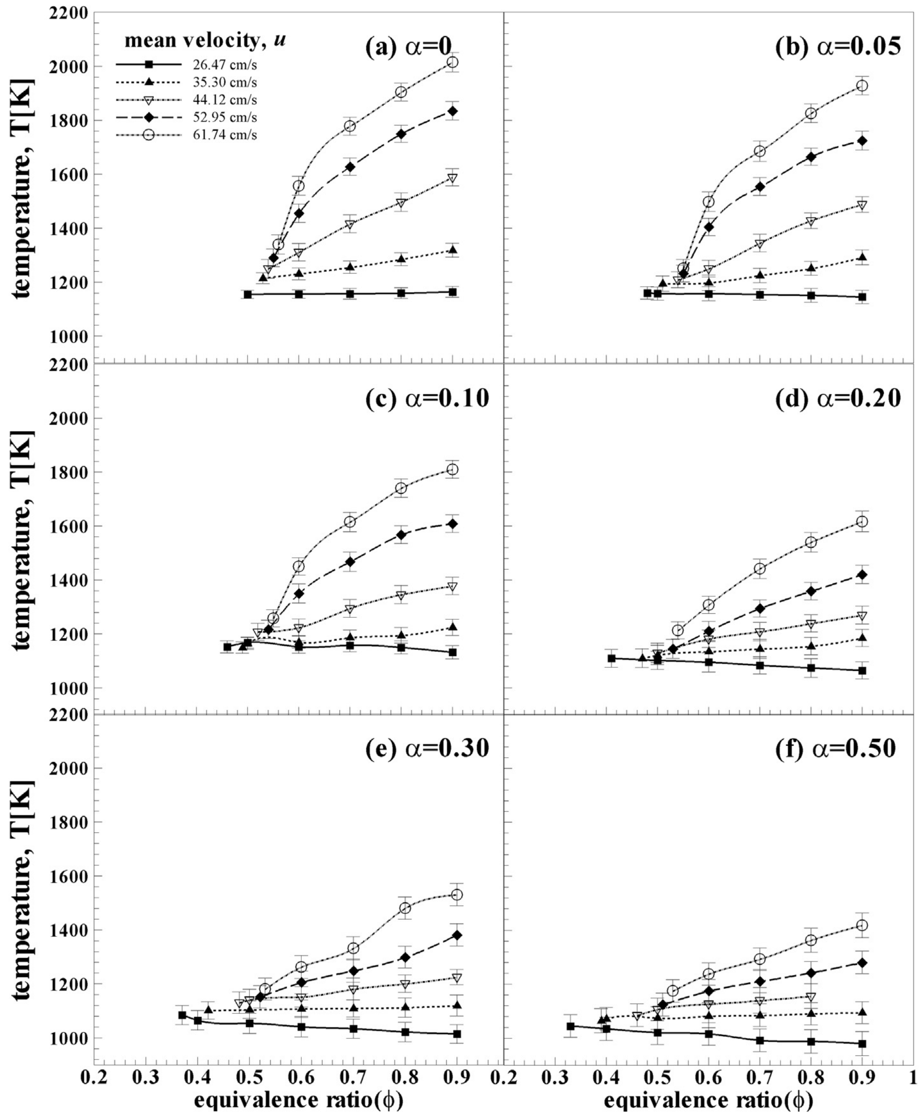

Fig. 4 – The effect of mean velocity and equivalence ratio on flame temperature in the presence of differing H_2 concentrations.

as the average of the three peak temperatures measured by the thermocouple. The error bar was generated based on the root mean square (RMS) of five experimental results obtained under the same operating conditions. When $\alpha = 0$ and $u = 61.74$ cm/s, the premixed H_2/C_3H_8/air flame temperature decreased as ϕ decreased; when u decreased, the flame temperature correspondingly decreased and the influence of the equivalence ratio on the flame temperature decreased. As α increased, the flame temperature decreased; ϕ exerted less influence on the flame temperature when α and u had higher values. These results indicated that adding H_2 to the premixed flame in the CGB decreased the flame temperature. Furthermore, when α increased, the influence of u and ϕ on the premixed flame decreased. The reason for the difference is that H_2 diffusivity [29] and the heat transfer mechanism in CGBs [2] changed, causing variations to the flame characteristics, details of which are explored in the following sections.

The influence of operating conditions on the S_{ab} of premixed H_2/C_3H_8/air flame in the ceramic granular bed

Previous research [2] has explored the speed at which premixed flames flash back, moving toward the CGB located upstream. The current study involved using the time difference between TC1 and TC5 measurements as the basis for calculating the S_{ab} of the premixed flame in the CGB. Fig. 5 shows the relations between the S_{ab}, u, and ϕ of the premixed H_2/C_3H_8/air flame (with varying α values) in the CGB. When $\alpha = 0$ and $u = 61.74$ cm/s, the S_{ab} of the premixed H_2/C_3H_8/air decreased as ϕ decreased. Moreover, the extent of the decrease was greater than that of the flame temperature. When u decreased, S_{ab} correspondingly decreased. A lesser effect of ϕ on S_{ab} was observed. When α increased, S_{ab} correspondingly increased; a high α value and low u value decreased the influence of ϕ on S_{ab}. These results suggested that adding H_2 to a premixed flame in CGB decreases the flame temperature. Additionally, the influence of u and ϕ on

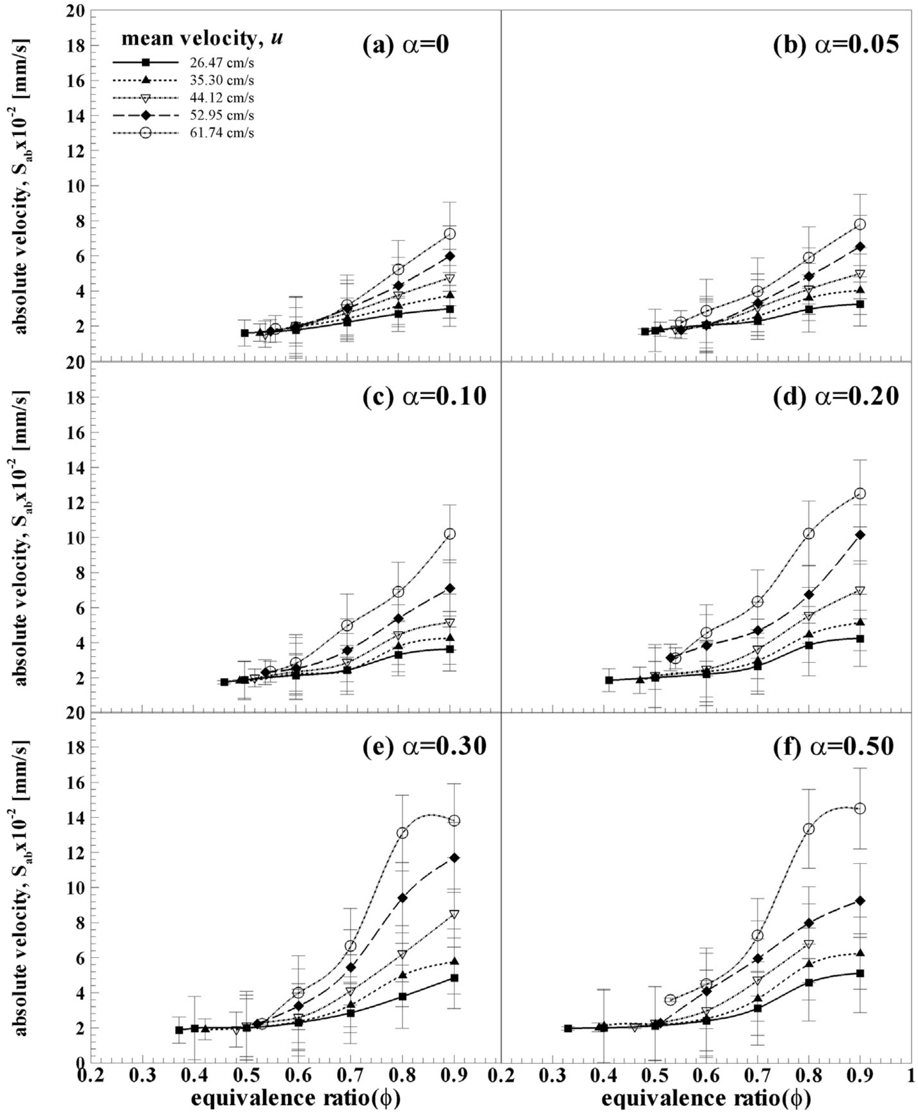

Fig. 5 – The effect of mean velocity and equivalence ratio on the absolute flame front velocity, S_{ab} in the presence of differing H_2 concentrations.

premixed flames decreased as α increased. These changes were also caused by the diffusivity of H_2 and changes to the heat transfer mechanism [2] in CGB, which caused the flame characteristics to vary. This phenomenon is further described in the following section.

The influence of H_2 on the premixed H_2/C_3H_8/air flame temperature

Fig. 6 shows the flame temperatures of premixed flames in the CGB when $\alpha = 0$ and 0.05 at various equivalence ratios. In the CGB, the temperature of the premixed H_2/C_3H_8/air flame was lower than that of a free flame [34]. When ϕ was high ($\phi \approx 0.9$), the flame temperature decreased substantially with decreasing u. As ϕ decreased, the difference between the flame and free flame temperature was not significant. When u decreased, the influence of ϕ on the free flame ($\alpha = 0$) temperature decreased (empty symbols). Similar to the case described in Ref. [2], the transfer of the premixed H_2/C_3H_8/air

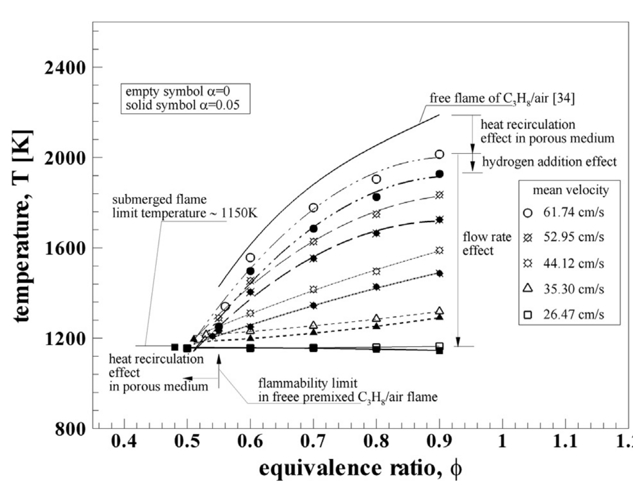

Fig. 6 – The influence of H_2 on the temperature of premixed H_2/C_3H_8/air flames in the CGB.

flame in the CGB effectively increased its flammability because the heat accumulation property of the ceramic granules caused the flames to exhibit mild combustion, which decreased the flame temperature and enhanced flammability. The temperature of the premixed H_2/C_3H_8/air flame in the CGB was lower when $\alpha = 0.05$ (solid symbols) than when $\alpha = 0$. This temperature difference decreased as u decreased, demonstrating a trend opposite to that observed previously (i.e., the temperature of the free flame was higher than that of premixed flame containing H_2). Moreover, in CGBs, the premixed flame temperature decreased as the equivalence ratio decreased. When u was low ($u = 26.47$ cm/s), the flame temperature decreased slightly as ϕ increased. This resulted primarily from the diffusivity of H_2 and the changes to the heat transfer mechanisms within the premixed flame, ceramic granules, and the premixed mixture in the CGB, which altered the flame structure.

The influence of H_2 on the flammability of premixed H_2/C_3H_8/air flames in the ceramic granular bed

The operating conditions (ϕ and u) affect the characteristics of premixed flames in CGBs. To determine how adding H_2 affects the Γ values, the Γ calculation method was employed (Eq. (2)) [2], to examine the effects of various α values on premixed H_2/C_3H_8/air flame flammability. Fig. 7 shows the firing rate and flammability of a premixed flame for various α values; the error bar was generated based on the errors caused by the flow rate of the premixed mixture and the equivalence ratio of the premixed flames. When $\alpha = 0$, the flammability (ϕ_f) of the premixed flame extended from 0.56 to 0.50 as the firing rate decreased. This change was associated with the thermal conduction mechanism in the CGB. At a low mean velocity, when the premixed mixture entered the CGB, it approached the quenching boundary and the flame temperature was low. The proportion of thermal radiation in the heat recirculation process was relatively low. By contrast, thermal conduction dominated the heat recirculation in the CGB [2]; hence, the flammability increased as the firing rate decreased. When α increased, the flammability of the premixed H_2/C_3H_8/air flame clearly increased. When $\alpha = 0.50$ and $\Gamma = 2.14$ kJ/s, the flammability ϕ equaled 0.53. As Γ decreased to 0.58 kJ/s, the flammability ϕ extended to $\phi = 0.33$. Fig. 7 shows that when the Γ value was high (2.14–2.21 kJ/s), the flammability of the premixed H_2/C_3H_8/air flame ranged between $\phi = 0.56$ and 0.53; when the Γ value was low (0.58–0.85 kJ/s), the flammability of the premixed H_2/C_3H_8/air flame was in the range of $\phi = 0.50$ to 0.33. Two factors might have caused this phenomenon. First, at low Γ operating ranges, the addition of H_2 can effectively extend the flammability and decrease the Γ of a CGB. High α of premixed H_2/C_3H_8/air indicates a lower global activation energy, which leads to ignition, thereby extending flammability. Second, thermal conduction in a CGB controls the heat recirculation in the CGB, which influences the flammability of premixed fuels with differing concentrations. When identical fuel concentrations were used, a low firing rate caused a low mean velocity (i.e., high thermal conduction during the preheat recirculation process). When the firing rate decreased and thermal conduction increased, the effects resulting from H_2 addition increased. Because the mass diffusivity of H_2 is higher than that of C_3H_8, when the mean velocity is low and conduction dominates heat recirculation, H_2 tends to diffuse into the upstream region, extending the flammability.

The influence of H_2 on flame temperature in the ceramic granular bed at various firing rates

Fig. 6 shows that adding H_2 decreased the flame temperature. Therefore, the relationship between Γ and the flame temperature in the CGB must be examined in detail. Fig. 8 shows the relationship between the flame temperature of premixed H_2/C_3H_8/air (with various α values) and Γ values. The relation between Γ and flame temperature can be divided into two operating conditions: low Γ (<1.56 kJ/s) and high Γ (>1.56 kJ/s). Under low Γ operating conditions, when the H_2 proportion was low ($\alpha = 0$, 0.05, 0.10), the flame temperature did not change with Γ, remaining at approximately 1150 K. When α increased, the flame temperature decreased considerably as Γ increased. Under high Γ operating conditions, the flame temperature increased as Γ increased, and decreased moderately as α increased. The primary reason that Γ affected the distribution of the flame temperature was that, at low Γ,

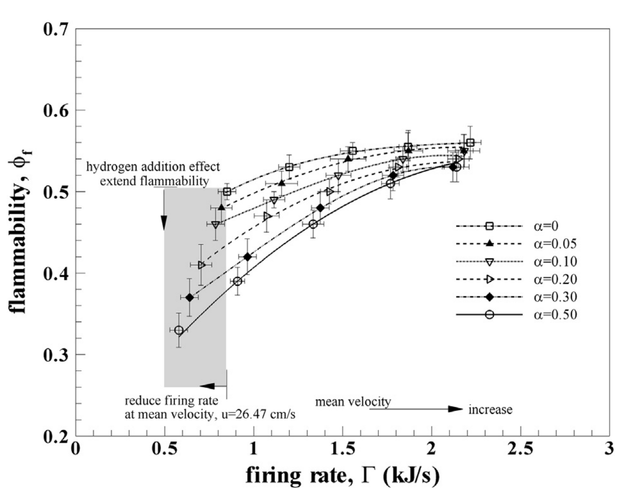

Fig. 7 – The influence of H_2 on the flammability of premixed H_2/C_3H_8/air flames in the CGB.

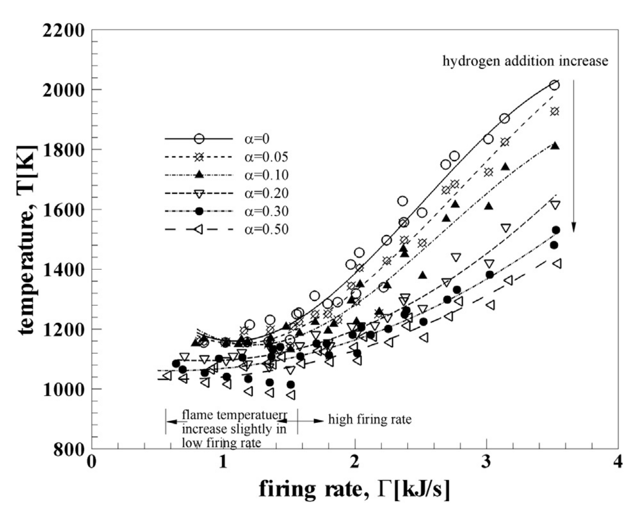

Fig. 8 – The influence of firing rate on the temperature of premixed H_2/C_3H_8/air flames in the CGB.

thermal conduction dominated heat recirculation in the CGB, but at high Γ, thermal radiation dominated. The reason for the difference is the mass diffusivity of H_2. Of the gas molecules in the premixed mixture, H_2 is the smallest; therefore, H_2 easily diffuses in the flame reaction zone. Furthermore, its high activity and low activation energy expands the premixed H_2/C_3H_8/air flame, increasing the thermal radiation loss of the flame. Consequently, under low Γ operating conditions, the flame temperature decreases with increasing Γ. Under operating conditions of high Γ, radiation heat transfer occurs; thus, increased Γ in the CGB increases the flame temperature. However, earlier results of this study indicated that adding H_2 decreased the flame temperature of the premixed H_2/C_3H_8/air in CGBs because the heat recirculation properties and the diffusivity of H_2 caused the premixed H_2/C_3H_8/air flame in the CGB to demonstrate mild (i.e., flameless) combustion, and therefore the flame temperature decreased with increasing α.

The influence of firing rate on S_{ab} in the ceramic granular bed

According to [2], when premixed CH_4/air is transferred in CGBs, changes in Γ affect the heat transfer mechanisms within the premixed flame and reactants, and also in the CGB, resulting in changes to the S_{ab} of the premixed flame in the CGB. In this study, when various H_2 concentrations were added to premixed C_3H_8/air flames and when u and ϕ remained constant, the Γ value slightly decreased (Fig. 9). When $\alpha = 0$, S_{ab} increased as the firing rate increased. Furthermore, S_{ab} increased with increasing α. Under low Γ operating conditions, an increase in α did not significantly affect S_{ab}, but under high Γ operating conditions, Γ and α significantly influenced S_{ab}. Because of the low mass diffusivity of H_2, the decreased global activation energy of the premixed mixture, and the influence of the heat transfer mechanism in the CGB, the speed at which the premixed flame moves upstream increases. At low firing rates, the thermal conduction effect of the premixed flame in the CGB was significant; however, at high firing rates, the thermal radiation dominated the propagation of the premixed flame. The heat transfer speeds of thermal conduction and radiation in CGB differed widely; thus, in a low firing rate regime, the flame S_{ab} increased slowly, and the effect of α on S_{ab} was not significant. In a high-firing-rate regime, α and Γ significantly influenced S_{ab}.

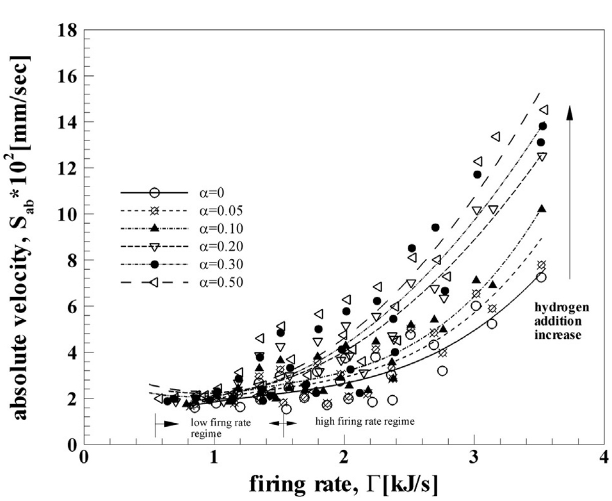

Fig. 9 – The influence of firing rate on the S_{ab} of premixed H_2/C_3H_8/air flames in the CGB.

Numerical simulation results

The following sections describe how H_2 affected the structure of premixed H_2/C_3H_8/air flame for $\phi = 0.7$; various u (44.12 m/s, 26.47 cm/s) and α (0, 0.1) values were used.

The effect of adding H_2 on the structure of the premixed H_2/C_3H_8/air flame in the ceramic granular bed at a high mixture velocity

Yang and Hsu [2] used numerical simulation to investigate the effects of the firing rate on the transfer mechanism of premixed CH_4/air flames in CGBs. The firing rate affected the transfer characteristics, altering the flame structure and heat recirculation. Fig. 10 shows the structure of premixed H_2/C_3H_8/air flames in a CGB where $\phi = 0.7$, $u = 52.95$ cm/s, $\alpha = 0$, and $\Gamma = 2.362$ kJ/s. Considering the gas temperature distribution, the temperature in the upstream region ($x/X = 0.62$) gradually increased, and then dramatically increased in the downstream location ($x/X = 0.49$). When the reactant mixture neared the reaction zone (Fig. 10a), the temperature increased rapidly, and the level of C_3H_8 and O_2 also increased. It is thus implied that CO_2, H_2O, and H_2 formed rapidly in this region. The peak CO value occurred downstream of the reaction zone.

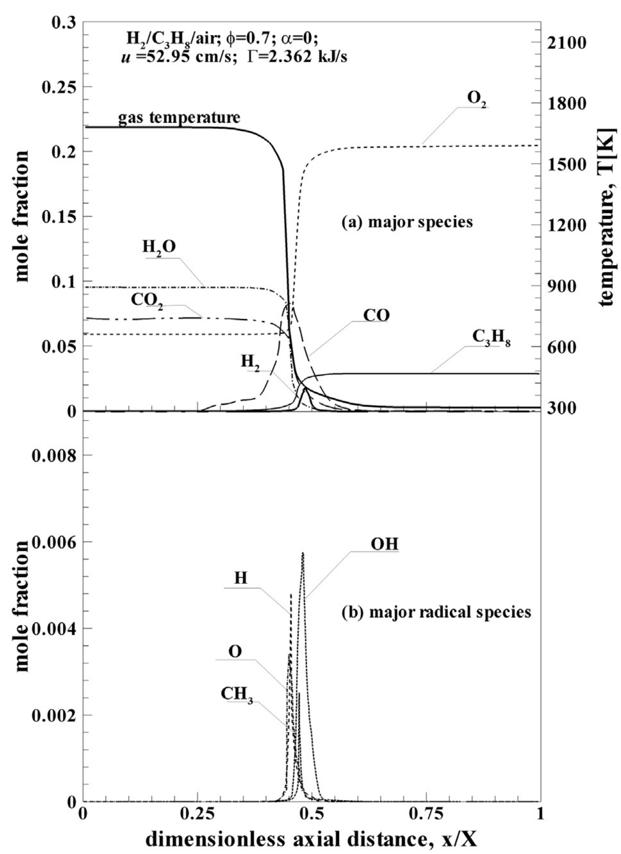

Fig. 10 – Premixed H_2/C_3H_8/air flame structure at a high mixture velocity in the CGB ($\alpha = 0$): (a) major species; (b) major radical species.

The level of H_2 gradually increased at $x/X = 0.62$, reaching a peak value at $x/X = 0.48$ (Fig. 10a). The H_2 value peaked near the location where temperature rapidly increased, indicating that the H_2 produced by C_3H_8 combustion influenced the characteristics of the reaction zone. The peak OH value occurred at $x/X = 0.47$, and peak values for CH_3, H, and O were also observed close to this region (Fig. 10b).

Under the same operating conditions, adding H_2 ($\alpha = 0.10$) to the premixed C_3H_8/air flame in the CGB affected the flame structure (Fig. 11) and generated $\Gamma = 2.37$ kJ/s. Furthermore, adding H_2 to the premixed mixtures prompted an increase in H_2 at $x/X = 0.59$, reaching a peak value at $x/X = 0.54$ (Fig. 11a). The mole fraction of C_3H_8 and O_2 began to decrease at $x/X = 0.61$, and significantly declined at $x/X = 0.52$. The flame temperature substantially increased at $x/X = 0.52$. The level of CO gradually increased at $x/X = 0.58$, reaching its peak value at $x/X = 0.46$, and decreased thereafter. When the level of CO peaked, the amount of CO_2 increased dramatically, yielding H_2O at an earlier stage in the process. Considering the distribution of the major radical species (Fig. 11b), the peak value for CH_3 appeared at $x/X = 0.53$, followed by those for H, O, and OH.

Compared with a premixed flame containing no H_2, at a high mean velocity ($u = 44.12$ cm/s), adding H_2 caused the peak value for H_2 to appear in the upstream location, which initiated the reaction between C_3H_8 and O_2, dispersing the remaining major radical species and expanding the overall flame reaction zone. These changes led to substantial heat loss; therefore, compared with premixed flames that lack H_2, premixed flames that contain H_2 demonstrate lower temperatures. Furthermore, compared with C_3H_8, H_2 demonstrates higher mass diffusivity and lower global activation energy levels. Thus, the presence of H_2 initiated the reaction of the fuel mixture, thereby increasing S_{ab}.

The effect of adding H_2 on the structure of the premixed H_2/C_3H_8/air flame in the ceramic granular bed at a low mixture velocity

The transfer characteristics of premixed flames in CGBs are affected by Γ values. Fig. 12 shows how various α values affect the structure of premixed flames in the CGB under low u conditions. When $u = 26.47$ cm/s, $\alpha = 0$, and $\Gamma = 1.181$ kJ/s, the heat transfer properties of the CGB influenced the premixed H_2/C_3H_8/air flame, expanding the combustion reaction zone (Fig. 12a). This transfer characteristic is similar to that of premixed CH_4/air in CGBs [18]. The flame temperature slowly increased at $x/X = 0.84$ until $x/X = 0.79$, at which point the temperature rapidly increased. The flame temperature peaked at $x/X = 0.39$ and subsequently decreased. According to the distribution of major species, C_3H_8 and O_2 dissociated at approximately $x/X = 0.67$, lowering their concentration. The point at which CO_2 and H_2 formed was around the point at which C_3H_8 and O_2 concentrations decreased. The H_2 and CO peaked at $x/X = 0.50$ and $x/X = 0.41$, respectively. The peak value for H_2 appeared at a distinct point from that at which the

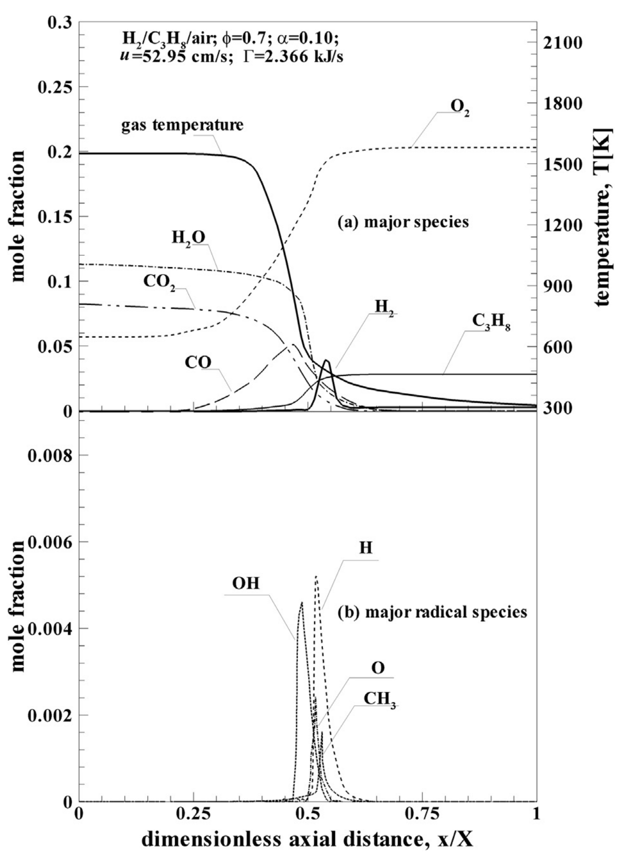

Fig. 11 — Premixed H_2/C_3H_8/air flame structure at a high mixture velocity in the CGB ($\alpha = 0.10$): (a) major species; (b) major radical species.

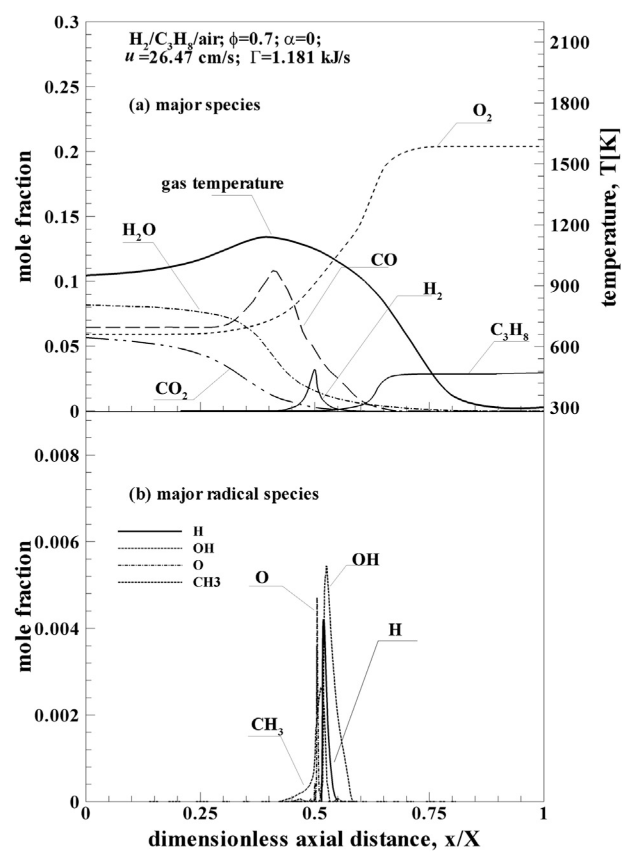

Fig. 12 — Premixed H_2/C_3H_8/air flame structure at a low mixture velocity in the CGB ($\alpha = 0$): (a) major species; (b) major radical species.

temperature rapidly increased, indicating that with a low mixture velocity, the heat transfer mechanism caused an increase in gas temperature. However, this temperature was not sufficiently high to initiate C_3H_8 combustion (i.e., C_3H_8 and O_2 react only when a certain temperature is reached). Furthermore, the region where H_2 is produced influenced the characteristics of the reaction zone. The peak value for OH appeared at $x/X = 0.47$, and those for CH_3, H, and O appeared thereafter (Fig. 10b). Compared with the high velocity condition ($u = 52.95$ cm/s and $\alpha = 0$), at a low mixture velocity, the major radical species in the premixed H_2/C_3H_8/air flames distributed across the upstream region. The peak value for OH appeared first, followed by those for H, O, and CH_3. This result indicated that generation of the OH radical is easily influenced by temperature, whereas the effects of temperature on CH_3 formation were not significant. In other words, at a low flow rate, the premixed flame exhibited mild combustion (i.e., the flame thickened, leading to the flameless phenomenon) because of changes to the heat transfer mechanism. When a flame suffers excessive heat loss, flame combustion is incomplete and emissions increase. This phenomenon is particularly obvious compared with a premixed CH4/air flame [2]. Therefore, the flame reaction zone cannot be distinguished from the preheating zone, which indirectly caused nonsignificant differences between the reactants and products. Consequently, the radical distribution in the reaction zone differed because of changes to the heat transfer mechanism.

Fig. 13 shows the structure of a premixed H_2/C_3H_8/air flame ($u = 26.47$ cm/s, $\phi = 0.7$, $\alpha = 0.10$) in the CGB at a low flow rate. Fig. 13a shows the distribution of major species and flame temperatures when the Γ value of H_2 increased from 1.181 kJ/s ($\alpha = 0$) to 1.183 kJ/s. The flame structures, flame temperature, and distribution of major species for premixed flames that included H_2 ($\alpha = 0.10$) and lacked H_2 ($\alpha = 0$) exhibited no significant differences. Moreover, increasing the Γ value decreased the concentrations of C_3H_8 and O_2 at the point before $x/X = 0.79$, causing the flame temperatures to increase in the downstream region. Adding H_2 into the premixed mixture caused the H_2 to peak before $x/X = 0.72$. The distribution of this peak was broad, which increased the concentration of H_2, thereby igniting the premixed mixture and increasing the temperature. The temperature distribution was wide, yielding the flameless phenomenon, which corresponded to that observed in the experiment. The distribution of major radical species demonstrated significant differences because H_2 addition and the heat transfer characteristics of CGB caused a broad radical distribution and a low peak value (Fig. 13b). According to the sequence in which the peak values for CH_3, H, O, and OH appeared, because of the broad temperature distribution across CGB, the high mass diffusivity and low global activation energy of H_2 triggered an early reaction, producing CH_3, followed by H, O and OH. Although these factors accelerated the formation of the flame reaction zone, the operating conditions also resulted in the flameless phenomenon. Furthermore, the heat transfer mechanism of CGB is dominated by thermal conduction, the speed of which is slower than that of thermal radiation. Therefore, adding H_2 exerted little influence on the decreasing flame temperature and increasing S_{ab} of the premixed H_2/C_3H_8/air flame with low mean velocity.

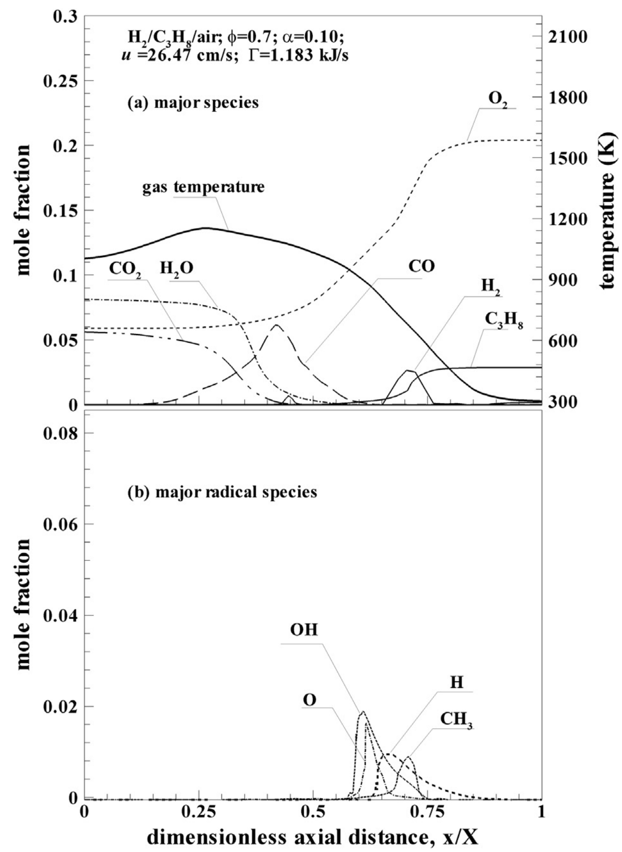

Fig. 13 – Premixed H_2/C_3H_8/air flame structure at a low mixture velocity in the CGB ($\alpha = 0.10$): (a) major species; (b) major radical species.

Conclusion

H_2 demonstrates high mass diffusivity and low activation energy; therefore, this study examined how H_2 concentration affects the transfer characteristics of premixed H_2/C_3H_8/air flames in CGBs through both experimental measurements and numerical simulations. The results are detailed as follows:

(1) When premixed hydrocarbon flames pass through a CGB, their flammability increases and temperature decreases. Adding H_2 to premixed hydrocarbon flames further increases flammability and decreases temperature in CGB.
(2) When the firing rate is high and Γ increases, adding H_2 causes a significant decrease of flame temperature and an increase of S_{ab}.
(3) When the firing rate is low and Γ increases, adding H_2 exerts little influence on the flame temperature and S_{ab}.
(4) When premixed flames are transferred in a CGB and the firing rate is high, the dominant heat transfer mechanism in the CGB is thermal radiation; thus, heat transfers are obvious and flame reaction zones converge. Because of H_2 properties, reaction zones are shifted to the upstream regions and flame thickness and the

amount of heat loss are increased. Thus, adding H_2 decreases flame temperature and increases the S_{ab}.

(5) When Γ is low, the dominant heat transfer mechanism in the CGB is thermal conduction; thus, heat transfer is not obvious and the flame reaction zones are wide. Although adding H_2 moves the flame reaction zones upstream, the heat transfer mechanism poses restrictions, thus mitigating the effects of adding H_2 with a low Γ on the premixed flames.

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